Unsteady Transonics of a Wing with Tip Store

Guru P. Guruswamy*
Sterling Software/Informatics, Palo Alto, California
and
Peter M. Goorjian† and Eugene L. Tu‡
NASA Ames Research Center, Moffett Field, California

The presence of tip stores influences both the aerodynamic and aeroelastic performances of wings. Such effects are more pronounced in the transonic regime. In this study, a theoretical method is developed, for the first time, to compute unsteady transonics of oscillating wings with tip stores. The method is based on the small-disturbance aerodynamic equations of motion from the potential-flow theory. To validate the method, subsonic and transonic aerodynamic computations are made for a wing of low aspect ratio, and they are compared with the available experimental data. The comparisons are favorable. The strong effects of the tip store on the transonic aerodynamics of the wing are also illustrated. The method developed in this study can be used for transonic aeroelastic computations of wings with tip stores.

Introduction

TIP stores are placed on aircraft either for fuel storage or as weapons such as tip missiles. Tip stores change the aerodynamic and aeroelastic characteristics of wings because of their aerodynamic inertia and elastic coupling with the wing. The influence of the tip store on the wing's unsteady aerodynamic characteristics can be pronounced in the transonic regime because of the presence of shocks. The detailed wind tunnel experiments[1] conducted at the National Aerospace Laboratory of the Netherlands (NLR) under the sponsorship of the U.S. Air Force have illustrated the strong influence of the tip missile on the unsteady transonics of the F-5 wing.

To date, the tip store has been theoretically modeled for linear subsonic and supersonic flows.[2] For the first time, a tip store is theoretically modeled for the nonlinear, unsteady, transonic flow regime with moving shock waves. This capability is required to investigate the transonic unsteady aerodynamics and aeroelasticity of fighter wings with tip stores. Studies[3] have shown that it is important to account for the aerodynamics of the tip store for correct computations of flutter speed.

An accurate computation of flutter speeds is important in the design and performance of aircraft. A typical flutter analysis requires several unsteady aerodynamic computations. Such computations are quite expensive in the transonic regime. To date, codes based on the three-dimensional transonic small-perturbation (TSP) theory have resulted in practical production codes[4] such as ATRAN3S, which is a highly improved parallel NASA Ames version of the original U.S. Air Force code,[5] XTRAN3S. Keeping practical aeroelastic applications in view, in this study the tip store is modeled using the transonic small-disturbance theory.

The transonic unsteady small-disturbance code[4] ATRAN3S, developed at the NASA Ames Research Center, can successfully handle both fighter- and transport-type wings.[4-6] It is based on an alternating direction, implicit finite-difference method.[7] This code also has the capability of conducting static and dynamic aeroelastic computations by simultaneously integrating aerodynamic and structural equations of motion. The computational time required by ATRAN3S is practical for aeroelastic computations on realistic wings such as the B-1 wing.[8]

In this work a procedure is developed to model the tip store based on the small-disturbance equation and is incorporated into ATRAN3S. The procedure is validated by comparing the steady and unsteady transonic results with wind tunnel results available for the F-5 wing.[1] Effects of the tip missile on the steady and unsteady transonic flow of the F-5 wing are also studied.

Formulation of Unsteady Transonic Flow Equations

The three-dimensional, modified small-disturbance transonic unsteady equation of motion is given by[9]

$$A\phi_{tt} + B\phi_{xt} = [E\phi_x + F\phi_x^2 + G\phi_y^2]_x + [\phi_y + H\phi_x\phi_y]_y + [\phi_z]_z \quad (1)$$

where

$$A = M_\infty^2, \qquad B = 2M_\infty^2, \qquad E = 1 - M_\infty^2$$

$$F = -\tfrac{1}{2}(\gamma+1)M_\infty^2, \qquad G = -\tfrac{1}{2}(\gamma-3)M_\infty^2$$

$$H = -(\gamma-1)M_\infty^2$$

The flowfield boundary conditions used are

Far downstream: $\phi_x + k\phi_t = 0$ (2a)

Far upstream: $\phi = 0$ (2b)

Far above and below: $\phi_z = 0$ (2c)

Far spanwise: $\phi_y = 0$ (2d)

Wing root: $\phi_y = 0$ (2e)

Trailing vortex wake: $[\phi_z] = 0$ (2f)

$[\phi_x + k\phi_t] = 0$ (2g)

where [ ] denotes the jump in the quantity across the vortex sheet.

Presented as Paper 86-0010 at the AIAA 24th Aerospace Sciences Meeting, Reno, NV, Jan. 6-9, 1986; received Jan. 1, 1986; revision received April 15, 1986.

*Principal Analyst. Member AIAA.
†Research Scientist. Associate Fellow AIAA.
‡NASA Co-op Student Trainee. Student Member AIAA.

The thin wing surface flow tangency condition that is satisfied at the mean chord plane is given by

$$\phi_z = f_x + kf_t = 0 \qquad (3)$$

where $f(x)$ denotes the airfoil surface function, and $k=\omega c/U$ is the reduced frequency based on the full chord (ω is the frequency in radians per second, c is a reference chord length, and U_∞ is the free-stream velocity).

The previous equations are transformed by a modified grid transformation technique.[4]

Transformation for Swept Tapered Wings

Equation (1), which is ideal for rectangular wings, can pose problems for swept tapered wings. The dependence of the solution on the leading-edge mesh spacing poses a problem in the application to swept tapered wings. Maintaining a sufficiency fine mesh spacing along the leading edge of a swept wing in a Cartesian coordinate system is inefficient because of the large number of points required. The drawbacks of the Cartesian mesh were rectified by the use of a conventional shearing transformation technique.[10] This conventional shearing transformation was adequate for wings with large aspect ratios, large taper ratios, and low sweep angles. It posed stability and accuracy problems for wings with low aspect ratios, small taper ratios, and large sweep angles. The modified shearing transformation[4] overcame these disadvantages.

The modified shearing transformation is given by

$$\xi(x,y) = (x - x_{\rm LE})/p(x,y), \qquad \eta(y) = y, \qquad \zeta(z) = z \qquad (4)$$

where the function $p(x,y)$ is obtained by the procedure explained in Ref. 4.

The main requirement of any transformation for the finite-difference method used in ATRAN3S is that it map any given wing to a rectangular wing. This is satisfied in the modified shearing transformation by using the same conventional shearing transformation. The modification involves replacing the function $p(x,y)$ in Eq. (4) by the local chord c. However, away from the wing, $p(x,y)$ is devised such that the grid lines have the following properties: 1) Far-field physical boundaries to the flow region are independent of the planform and always form the boundaries of a rectangular box, with the upstream and downstream surfaces normal to the free stream; 2) smaller gradients are obtained for the metric quantities, particularly near the boundaries, and smooth first and second derivatives are obtained for the metric quantities; and 3) grid lines are clustered near the leading and trailing edges as before in the shearing transformation.

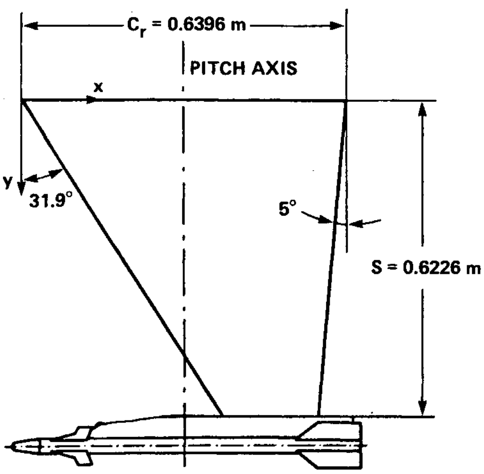

Fig. 1 Planform of the wing model.

After applying the transformation and rearranging, one can write Eq. (1) as

$$-[A\xi_x^{-1}\phi_t + B\phi_\xi]_t + [E\xi_x\phi_\xi + F\xi_x^2\phi_\xi^2 + G(\xi_y\phi_\xi + \phi_\eta)^2 + \xi_x^{-1}\xi_y(\xi_y\phi_\xi + \phi_\eta) + H\xi_y\phi_\xi(\xi_y\phi_\xi + \phi_\eta)]_\xi + [\xi_x^{-1}(\xi_y\phi_\xi + \phi_\eta) + H\phi_\xi(\xi_y\phi_\xi + \phi_\eta)]_\eta + [\xi_x^{-1}\phi_\zeta]_\zeta = 0 \qquad (5)$$

The differencing procedure for Eq. (5) is an extension of the Murman-Cole type-dependent difference procedure applied to an arbitrary coordinate system. Type-dependent differences are used only to approximate derivatives in the streamwise direction, and all other derivatives are approximated by central differences. This method approximates the rotated differencing developed by Jameson.[11] Thus the coefficient G is split into two components G_S and G_N such that Eq. (5) may be decomposed into streamwise and normal contributions to the spatial differencing. Equation (5) can now be written as

$$-[A\xi_x^{-1}\phi_t + B\phi_\xi]_t + [E\xi_x\phi_\xi + F\xi_x^2\phi_\xi^2 + (G_S + G_N)(\xi_y\phi_\xi + \phi_\eta)^2 + \xi_x^{-1}\xi_y(\xi_y\phi_\xi + \phi_\eta) + H\xi_y\phi_\xi(\xi_y\phi_\xi + \phi_\eta)]_\xi + [\xi_x^{-1}(\xi_y\phi_\xi + \phi_\eta) + H\phi_\xi(\xi_y\phi_\xi + \phi_\eta)]_\eta + [\xi_x^{-1}\phi_\zeta]_\zeta = 0 \qquad (6)$$

where

$$G = G_S + G_N, \qquad G_S = 1 - M_\infty^2, \qquad G_N = \tfrac{1}{2}(\gamma - 2)M_\infty^2 - 1$$

This equation is solved by the time-accurate alternating direction implicit scheme (see the section on "Computations of Unsteady Transonic Flows" in Ref. 7) extended to three dimensions.[4]

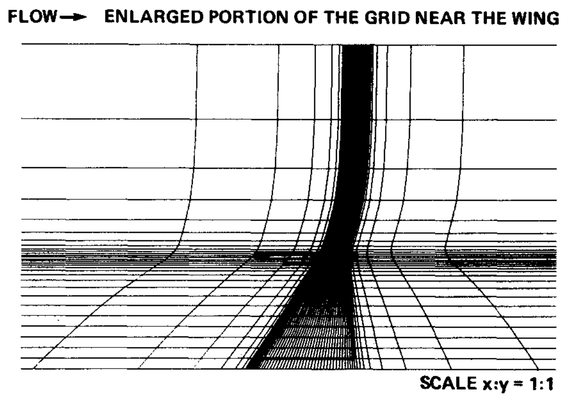

Fig. 2 Physical grid in the plane of the wing (64×30).

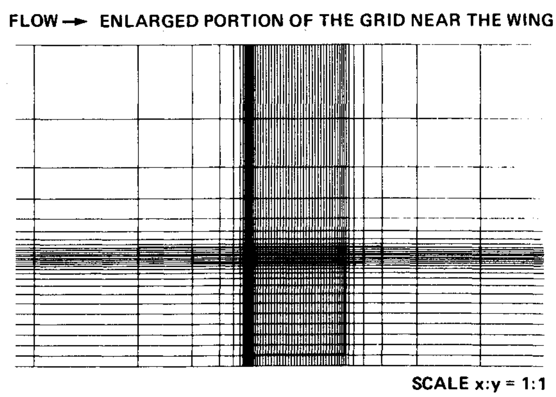

Fig. 3 Computational grid in the plane of the wing (64×30).

Modeling of the Tip Store

The tip store is modeled as a body based on the small-disturbance theory. For a body described by the equation $B(x,y,z,t)=0$, the small-disturbance flow tangency boundary condition on the surface of the body becomes (see p. 5 of Ref. 12)

$$kB_t + B_x + \phi_y B_y + \phi_z B_z = 0 \tag{7}$$

It is noted that most tip stores, such as the tip missile of a fighter wing, have diameters of the order of the wing thickness. Because of the fixtures, such as the launcher plate, it can be assumed that the store, when attached to the wing, acts more as an extension of the wing than as a body of revolution. For purposes of aerodynamic modeling it can be further assumed that the tip store is an extension of the wing in planform. This allows us to use a simplified flow tangency condition as follows.

For a planar body for which all points lie close to $z=0$, the flow tangency condition is simplified in this study to

$$\phi_z = f_x + kf_t \tag{8}$$

where $B=z-f(x,y,t)$.

Assumptions made in deriving Eq. (8) may not be suitable for very thick tip stores, such as fuel tanks. In this paper, it is assumed that the tip store can be treated as an extension of the wing, and as a result the flow tangency condition given by Eq. (8) is employed. Note that the flow tangency condition given by Eq. (8) is similar to the flow tangency condition of Eq. (3) on the thin wing. The tip store is modeled within the small-disturbance limitations as follows.

A physical grid is obtained based on the modified grid transformation of Eq. (4) for the wing without tip store. Then the planform of the tip store is mapped onto the physical grid. The flow tangency condition given by Eq. (3) is applied at all the grid points on the tip store. Thus the tip store is treated as an extension of the wing in solving the flow equations given by Eq. (5).

The small-disturbance, unsteady transonic aerodynamic equations given by Eq. (5) are solved for the tip store by the same alternating direction finite-difference scheme employed for the wing.

Results

In order to verify the modeling of the tip store, steady and unsteady transonic results were computed for the F-5 wing at various flow conditions and were compared with the wind tunnel results from NLR.[1]

Grid

The planform of the F-5 wing is given in Fig. 1. This wing, which has a low aspect ratio of 3.0 and a small taper ratio of 0.3, has a slender tip missile attached to it with a launcher plate. By using the modified shearing transformation developed at Ames, steady and unsteady transonic computations were made for the clean F-5 wing[4] which compared well with experiment.[1] The same transformation is employed in this report. The physical grid in the plane of the wing has 64 lines in the streamwise direction and 30 lines in the spanwise direction, as shown in Fig. 2. The tip missile region is represented by 6 span stations; in the vertical direction 40 grid lines are employed.

The planform of the tip missile is mapped onto the physical grid as shown in Fig. 2. Next, this physical grid is mapped into the Cartesian grid shown in Fig. 3. It is noted that the discontinuity in the planform is retained in the computational domain. By this method, metrics of the transformation matrix between the physical grid and the Cartesian finite-difference grid do not have discontinuities in spite of discontinuities in the planform. Continuous metrics are very important to obtain a stable and accurate flow solution.[4]

Computations of Steady Results

Steady aerodynamic pressures were computed by integrating Eq. (6) in time and setting the steady boundary conditions on the wing. The time step size (nondimensionalized by ω) required to obtain stable and accurate results for all the cases considered in this analysis was about 0.0075 based on a reduced frequency of $k=0.55$. This time step size was determined based on the numerical experiments conducted for the clean wing. Converged steady results were obtained with about 2000 iterations.

In Fig. 4, the steady results are given for the subsonic case at $M=0.80$ and $\alpha=0.5$ deg. The results from ATRAN3S compare well with the experiment. Figure 5 shows the comparison between the results from ATRAN3S and the experiment for

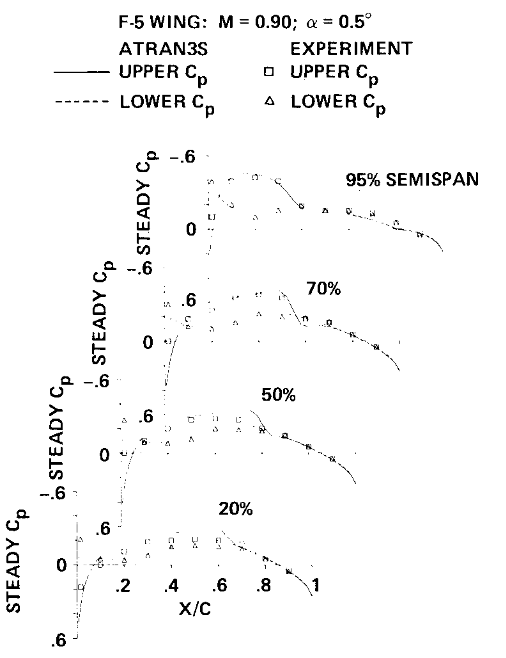

Fig. 4 Subsonic steady-pressure comparisons between theory and experiment at $M=0.80$ for the F-5 wing with a tip missile.

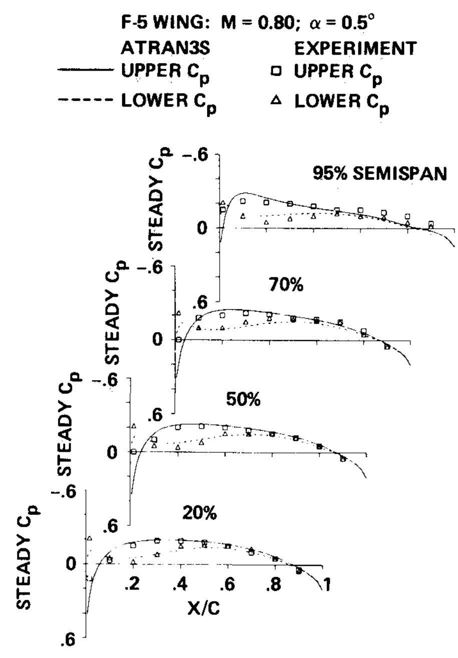

Fig. 5 Transonic steady-pressure comparisons between theory and experiment at $M=0.90$ for the F-5 wing with a tip missile.

the transonic case at $M=0.90$ and $\alpha=0.5$ deg. Comparisons are good for all the span stations, particularly for the 95% semispan station, which is very close to the tip store. Good comparisons at the 95% semispan station show that the tip store is modeled correctly in the code.

In Figs. 6 and 7, ATRAN3S steady pressures for the F-5 wing with and without tip missile are shown for $M=0.80$ and $M=0.90$, respectively. The same number of grid lines, $64\times30\times40$, was used for the clean wing; however, the grid lines in the spanwise direction were redistributed based on the planform of the wing alone.[4] The transonic case at $M=0.90$ has more influence of the tip missile on the steady pressures than the subsonic case at $M=0.80$. At $M=0.90$, notice the increase in the pressure peaks resulting from the stronger shock waves, particularly near the tip region. Figure 8 shows the quasi-steady lift coefficients $C_{1\alpha}$ for the wing with and without tip missile at $M=0.90$. These lift coefficients were computed at the zero mean angle of attack from the steady-pressure computations made at angles of attack of 0.5 and −0.5 deg. Presence of the tip missile generates about a 25% increase in lift when compared to the case of the clean wing. The corresponding increase in lift observed in the experiment[1] is about 20%.

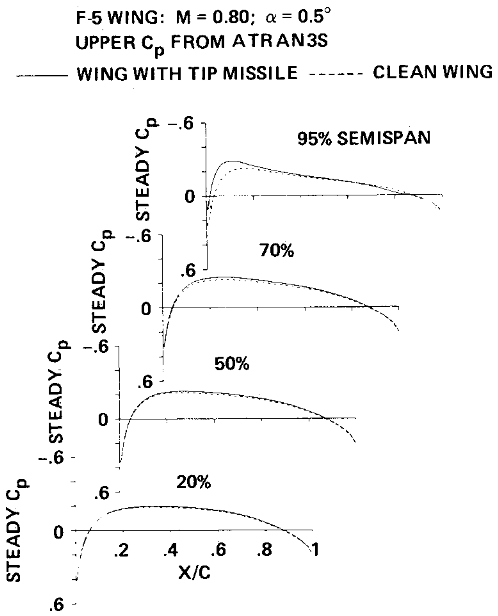

Fig. 6 Subsonic steady-pressure comparisons of the F-5 wing between the planforms at $M=0.80$ with and without a tip missile.

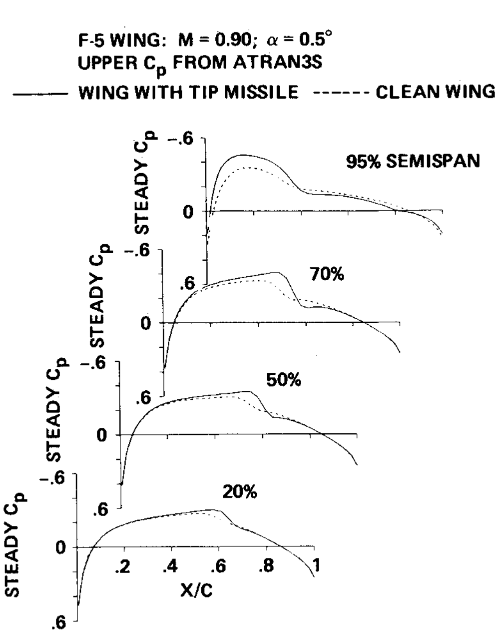

Fig. 7 Transonic steady-pressure comparisons of the F-5 wing between the planforms at $M=0.90$ with and without a tip missile.

Computations of Unsteady Results

Figure 9 shows the modal motion used in the NLR experiment. The wing is pitching about an axis located at the 50% root chord, and the pitching axis is normal to the wing root. In this study, all unsteady results were obtained for the wing oscillating at a frequency $f=40$ Hz. The same modal motion used in the experiment was simulated in the code. The unsteady aerodynamic equation of motion of Eq. (6) was integrated in time by using the time integration scheme available in ATRAN3S. The same time step size employed in the steady-state computations was employed for the computations (of the unsteady results.) From the earlier computations on the clean wing, it was observed that three cycles were required, during which time the transients disappeared and a periodic response was obtained. For all the unsteady cases studied here, (the computations) were made by forcing the wing to undergo a sinusoidal modal motion for three cycles, with 1500 time steps per cycle. Results from the third cycle were employed for comparison with the experiment.

Figures 10 and 11 show plots of the real and imaginary values of the upper-surface pressures at four span stations ob-

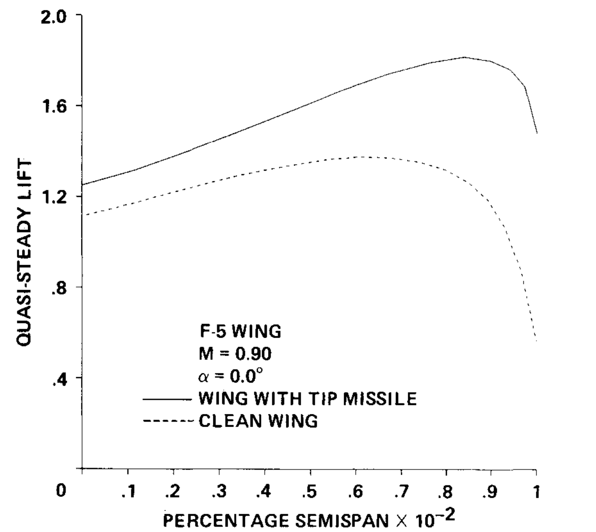

Fig. 8 Quasi-steady lift comparisons of the F-5 wing between the planforms at $M=0.90$ with and without a tip missile.

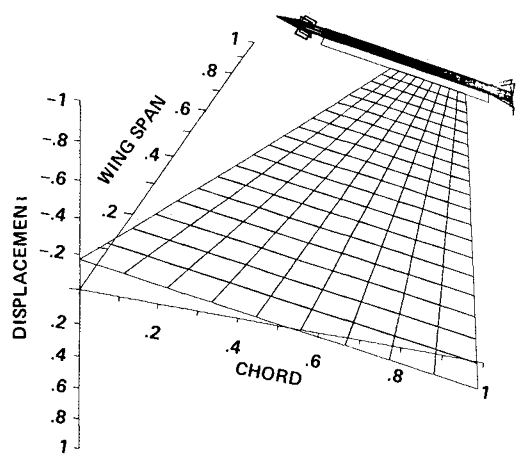

Fig. 9 Modal motion of the F-5 wing.

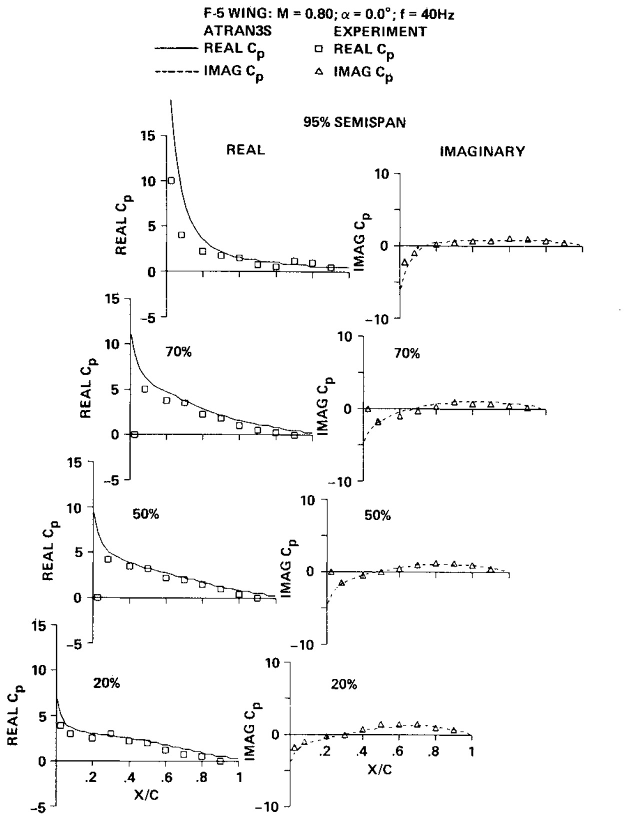

Fig. 10 Subsonic unsteady upper-surface pressure comparisons between theory and experiment at $M=0.80$ for the F-5 wing with a tip missile.

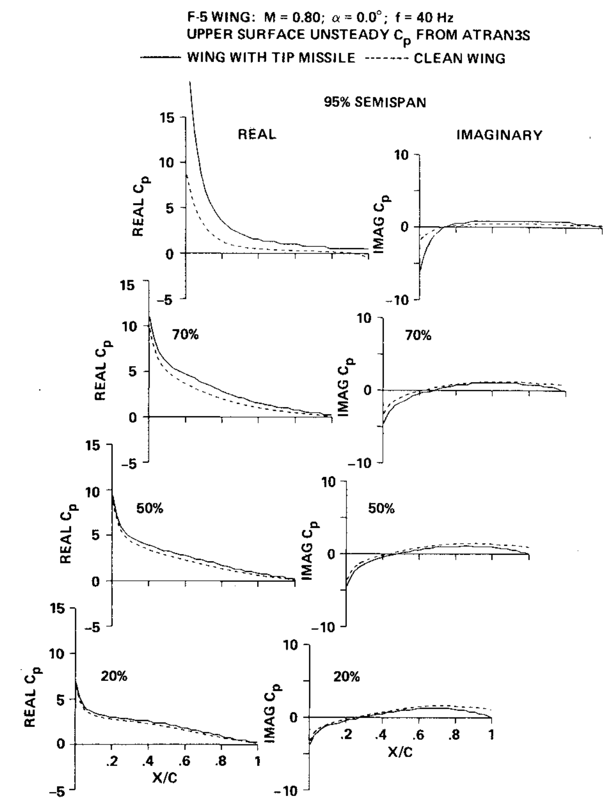

Fig. 12 Subsonic unsteady upper-surface pressure comparisons of the F-5 wing between the planforms at $M=0.80$ with and without a tip missile.

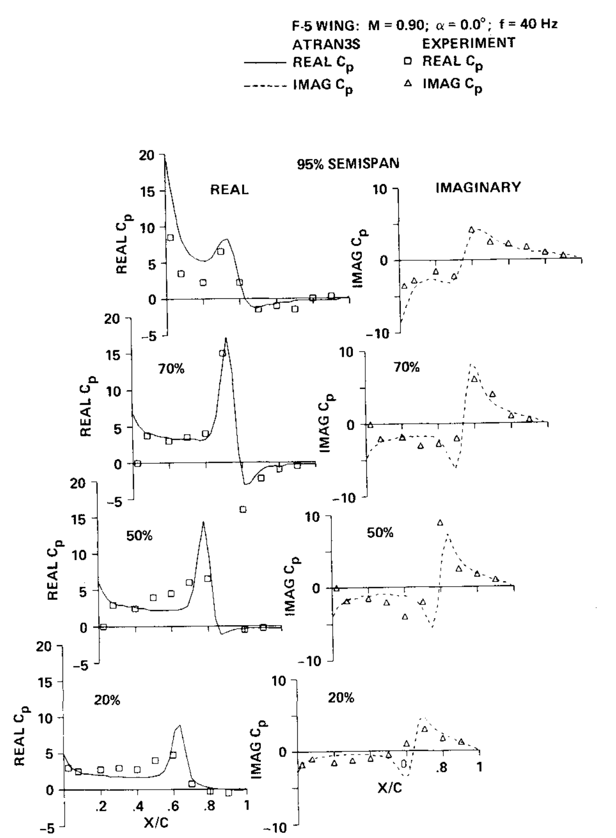

Fig. 11 Transonic unsteady upper-surface pressure comparisons between theory and experiment at $M=0.90$ for the F-5 wing with a tip missile.

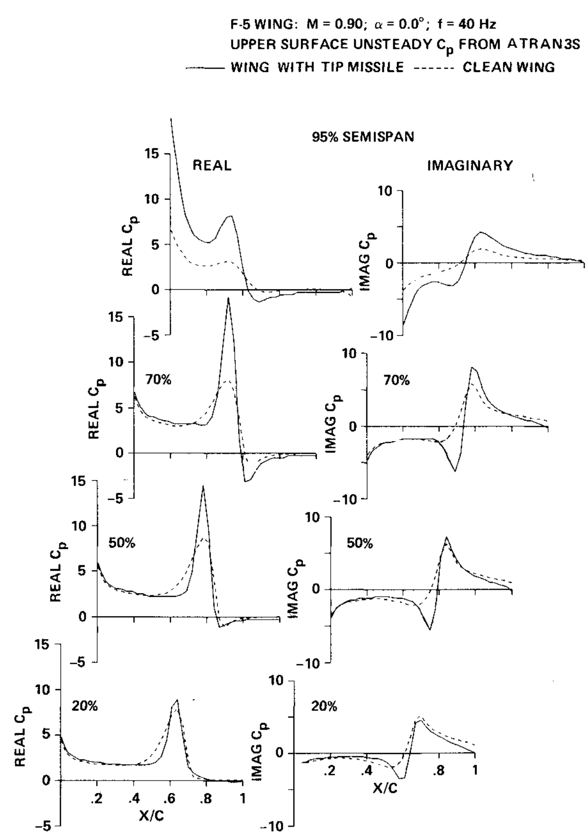

Fig. 13 Transonic unsteady upper-surface pressure comparisons of the F-5 wing between the planforms at $M=0.90$ with and without a tip missile.

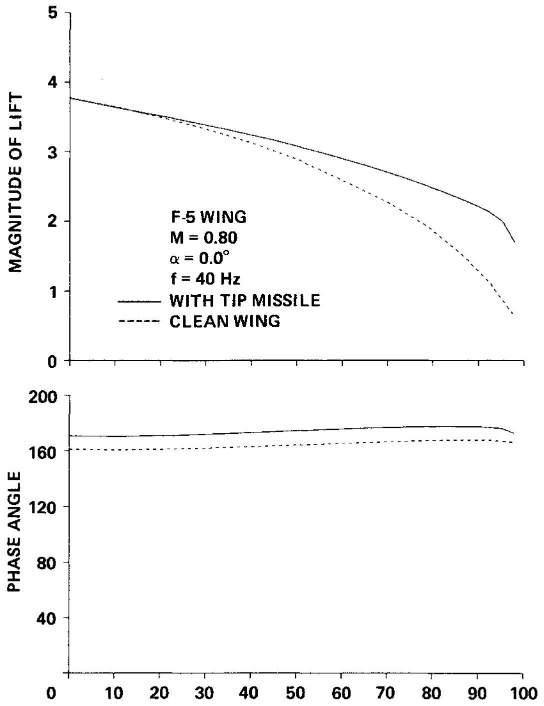

Fig. 14 Unsteady lift comparisons of the F-5 wing between the planforms at $M=0.80$ with and without a tip missile.

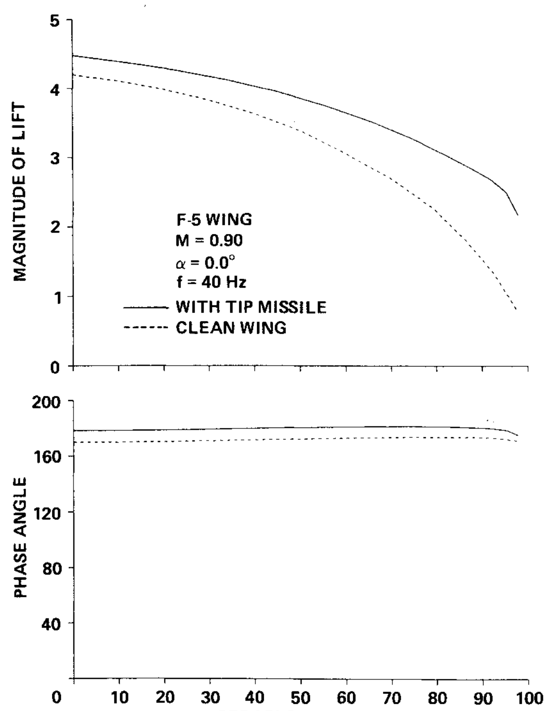

Fig. 15 Unsteady lift comparisons of the F-5 wing between the planforms at $M=0.90$ with and without a tip missile.

tained by the ATRAN3S at $M=0.8$ and $M=0.9$, respectively. These results were obtained for the wing with the tip missile oscillating at a frequency of 40 Hz. Figures 10 and 11 show that the unsteady results from ATRAN3S generally compare well with experiment for both subsonic and transonic cases. For both cases, the imaginary parts agree with experiment better than the real parts. Discrepancies in the real parts at the 95% semispan station may be due to the coarse grid on the tip missile in front of the leading edge.

Figures 12 and 13 show the comparison of unsteady results with the clean wing at $M=0.80$ and $M=0.90$, respectively. The strong effects of the tip store on unsteady pressures can be observed. The tip missile has more influence at the transonic Mach number than at the subsonic Mach number. For the transonic case, notice the increase in the pressure peaks, which was also shown by the experiment in Fig. 11. When Figs. 12 and 13 are compared with Figs. 7 and 8, it can be seen that tip missile has more influence on unsteady pressures than on steady pressures at both subsonic and transonic Mach numbers.

Figures 14 and 15 show the comparison of magnitudes and corresponding phase angles of unsteady lift coefficients $C_{l\alpha}$ between wings at $M=0.80$ and $M=0.90$, respectively, with and without the tip missile. At both Mach numbers the presence of the tip missile has a greater influence on the magnitude than on the phase angle of the unsteady lift coefficients. The transonic case at $M=0.90$ has more influence of the tip missile on the unsteady pressures than the subsonic case at $M=0.80$. These trends agree with the observations made in the experiment[1] at the 20-Hz frequency. The effects of the tip missile on the unsteady aerodynamics can change the flutter characteristics of the wing.

Conclusions

A procedure is developed to compute the unsteady transonics of an oscillating wing with a tip store. Keeping the practical aeroelastic applications in view, one can model the tip store by using the transonic small-disturbance theory and incorporating it into the TSD code ATRAN3S. Results from the code compare well with the steady and unsteady experimental results for the F-5 wing. This illustrates that the small-disturbance theory is adequate for thin wings with slender tip stores at small angles of attack. It is noted that flutter starts as a small-perturbation phenomenon, and the present method based on the small-disturbance theory can provide accurate data for predicting flutter speeds of wings with tip stores.

This study indicates that the tip missile has significantly more influence on the steady and unsteady pressures of the wing at transonic Mach numbers than at subsonic Mach numbers. Therefore it is important to account for the aerodynamics of the tip store for the accurate computation of the flutter speed in the transonic regime. Since the F-5 wing is representative of fighter wings, the results from this work will be quite useful in understanding the complex phenomenon of the transonic wing/store aerodynamics and flutter of fighter wings.

Acknowledgments

This work was supported through funding from Eglin Air Force Base and monitored by Bob Bunton, and the authors appreciate his helpful suggestions.

References

[1]Tijdeman, J., et al., "Transonic Wind Tunnel Tests on an Oscillating Wing with External Stores; Part III—The Wing with Tip Store," Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, OH, AFFDL-TR-78-194, May 1979.

[2]Sotomayer, W. A., Dusto, A. R., Epton, M. A., and Johnson, F. T., "Aerodynamic Modeling of an Oscillating Wing With External Stores," AIAA Paper 81-0648, May 1981.

[3]Turner, C. D., "A Study of The Effects of Store Aerodynamics on Wing/Store Flutter," AIAA Paper 81-0604, May 1981.

[4]Guruswamy, P. and Goorjian, P. M., "An Efficient Coordinate Transformation Technique for Unsteady Transonic Aerodynamic Analysis of Low Aspect Ratio Wings," *Journal of Aircraft*, Vol. 22, March 1985, pp. 193-199.

[5]Borland, C. J. and Rizzetta, D. P., "Transonic Unsteady Aerodynamics for Aeroelastic Applications, Volume I—Technical Development Summary for XTRAN3S," AFWAL-TR-80-3107, June 1982.

[6]Guruswamy, P., Marstiller, J. W., Yang, T. Y., and Goorjian, P. M., "Effects of Viscosity and Modes on Transonic Flutter Boundaries of Wings," *Journal of Aircraft*, Vol. 22, Sept. 1985, pp. 756-762.

[7]Goorjian, P. M., "Computations of Unsteady Transonic Flows," *Advances in Computational Transonic*, Vol. IV, edited by W. G. Habashi, Pineridge Press, Swansea, U.K., 1985.

[8]Guruswamy, P. and Swansea, U. K., Goorjian, P. M., "Transonic Aeroelastic Analysis of the B-1 Wing," AIAA Paper 85-0690-CP, April 1985.

[9]Yoshihara, H. "Formulation of the Three-Dimensional Transonic Unsteady Aerodynamic Problem," Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, OH, AFFDL-TR-79-3030, Feb. 1979.

[10]Ballhaus, W. F. and Bailey, F. R., "Numerical Calculation of Transonic Flow About Swept Wings," AIAA Paper 72-677, June 1972.

[11]Jameson, A., "Iterative Solution of Transonic Flows Over Airfoils and Wings, Including Flows at Mach 1," *Communications of Pure and Applied Mathematics*, Vol. 27, 1974, pp. 283-309.

[12]Landahl, M. T., "*Unsteady Transonic Flow,*" Pergamon, New York, 1961.